Progress in Photon Colliders *

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Abstract

Last two years were very important in history of a photon colliders. This option is included now in conceptual design reports of the NLC, JLC and TESLA/SBLC projects. All the designs foresee two interaction regions: one for e^+e^- and the second for $\gamma\gamma$, γe and e^-e^- collisions. This paper is focused on three aspects: 1) arguments for photon colliders; 2) parameters of current projects; 3) ultimate luminosities and energies, new ideas. Recent studies have shown that the main collision effect - coherent pair creation - is suppressed at photon colliders with the energy ($2E < 2$ TeV) due to the beam repulsion, and one can achieve, in principle, the $\gamma\gamma$ luminosity exceeding 10^{35} cm^{-2}s^{-1} . The required electron beams with very small emittances can be obtained, for example, using a laser cooling of electron beams. This new method requires a laser with a power by one order of magnitude higher than that required for the "conversion" of electrons to photons. Such lasers are not available today, but hopefully they will appear by the time when linear colliders will be built. High energy $\gamma\gamma$, γe colliders with the luminosity comparable to that in e^+e^- collisions are beyond the competition in study of many phenomena of particle physics.

1   Introduction

Let me remind briefly the basic scheme of a photon collider [1],[2], see fig.1. Two electron beams after the final focus system are traveling toward the interaction point (IP). At a distance of about 0.1–1 cm upstream from the IP, at the conversion point (C), the laser beam is focused and Compton backscattered by electrons, resulting in the high energy beam of photons. With reasonable laser parameters one can "convert" most of electrons into high energy photons. The photon beam follows the original electron direction of motion with a small angular spread of order $1/\gamma$, arriving at the IP in a tight

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focus, where it collides with the similar opposing high energy photon beam or with an electron beam. The photon spot size at the IP may be almost equal to that of electrons at IP and therefore, the luminosity of $\gamma\gamma$, γe collisions will be of the same order of magnitude as the "geometric" luminosity of basic *ee* beams. The detailed description of photon colliders properties can be found in refs [2]–[5] and in the Berkeley Workshop Proceedings [6].
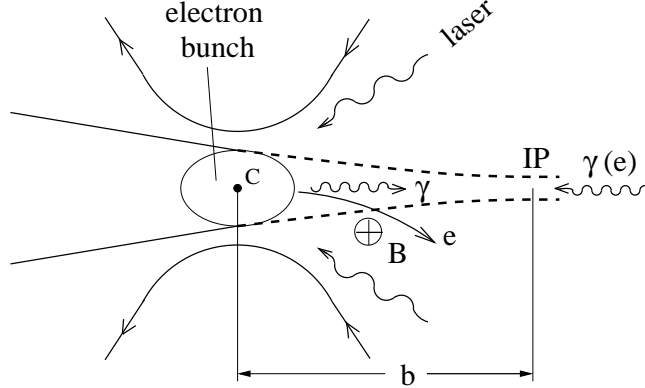

Figure 1: Scheme of $\gamma\gamma$; γe collider.

Now, this option is included into the Conceptual Design Reports of the NLC [7], TESLA–SBLC [8] and JLC [9]. All these linear collider projects foresee the second interaction region for $\gamma\gamma$,γe collisions. This is quite a success but for final decisions it is necessary to have very clear justification that photon colliders are realistic and can substantially add to a discovery potential of linear colliders. Below are some arguments for photon colliders.

1. Some phenomena can be studied at photon colliders better than anywhere, for example, the measurement of $\gamma\gamma \rightarrow$ Higgs width, which is sensitive to all heavy charged particles; study of the vertex $\gamma\gamma$WW.

2. Cross sections for the pair production of charged scalar, leptons and top in $\gamma\gamma$ collisions are larger than those in e^+e^- collisions by a factor of 5; for WW production this factor is even larger: 10–20.

3. In γe collisions charged supersymmetric particles with masses higher than in e^+e^- collisions can be produced (heavy charged particle plus light neutral).

4. The luminosity of photon colliders (in the high energy part of luminosity spectrum) with electron beam parameters considered in the present designs will be about 10^{33} cm^{-2}s^{-1} or by a factor 5 smaller than $L_{e^+e^-}$. But the absence of collisions effects at $0.1 - 1$ TeV photon colliders allows to reach $L_{\gamma\gamma}$ up to 10^{35} cm^{-2}s^{-1} using electron beams with very low emittances. High luminosity photon colliders can provide two orders high production rate of WW pair and other charged particles (see item 2).

5. Obtaining of the ultimately high luminosities requires the development of new techniques, such as the laser cooling of electron beams [12]. However, linear colliders

will appear (may be) only in one decade and will work next two decades. The upgrading of the luminosity requires the injection part modification only; it may be a separate injector for a photon collider, merging of many low emittance RF-photoguns (with or without laser cooling) is one of possible variants.

6. Linear colliders are very expensive facilities and their potential should be used in the best way. Two detectors (one for e$^+$e$^-$ and the other for $\gamma\gamma$ and γe) can give much more results than the simple doubling of statistics in e$^+$e$^-$ collisions with one detector .

7. Development of X-ray FEL lasers based on linear colliders (which are now under way) will favour the work on FEL required for photon colliders.

2 Physics potential, requirements to $\gamma\gamma$ luminosity

The physics in $\gamma\gamma$, γe colliders is very rich. The total number of papers devoted to the physics at photon colliders approaches to one thousand. Some examples are given in the introduction. Recent review of physics at photon colliders can be found in TESLA/SBLC Conceptual Design Report [8] and in the talk of G. Jikia at this workshop.

The resonance production of Higgs in $\gamma\gamma$ collisions and measurement of its $\gamma\gamma$ width is a task of primary importance.

Cross sections of the charged particle production in $\gamma\gamma$ collisions are higher than those in e$^+$e$^-$ collisions. At $E \gg Mc^2$ the ratio of cross sections are the following ($R_{XX} = \sigma_{\gamma\gamma \to X^+X^-}/\sigma_{e^+e^- \to X^+X^-}$): $R_{H^+H^-} \sim 4.5$; $R_{t\bar{t}} \sim 4$; $R_{W^+W^-}(|cos\vartheta| < 0.8) \sim 15$; $R_{\mu^+\mu^-}(|cos\vartheta| < 0.8) \sim 8.5$.

To have the same statistics in $\gamma\gamma$ collisions the luminosity may be smaller than that in e$^+$e$^-$ collisions at least by a factor of 5. Note that result in $\gamma\gamma$ and e$^+$e$^-$ collisions are complimentary even for the same final states because diagrams are different (for example, the vertex $\gamma\gamma$WW can be studied only in $\gamma\gamma$ collisions).

A reasonable scaling for the required $\gamma\gamma$ luminosity (in the high energy peak of the luminosity distribution) at $\gamma\gamma$ collider is

$$L_{\gamma\gamma} \sim 3 \times 10^{33} S(\text{TeV}^2), \text{ cm}^{-2}\text{s}^{-1}. \tag{1}$$

With such a luminosity one can detect 3.5×10^3 H^+H^-; 2×10^4 $\mu^+\mu^-(|cos\vartheta| < 0.8)$; 2×10^4 $t\bar{t}$; 2×10^5 $W^+W^-(|cos\vartheta| < 0.8)$; 2×10^6 $S(\text{TeV}^2)$ W^+W^- for the time $t = 10^7$ c . Somewhat larger luminosity ($\sim 10^{33}$) is required for the search and study of the "intermediate" ($M_H \sim 100 - 200$ GeV) Higgs boson.

With an electron beam considered in current projects [7], [8] with 2E∼500 GeV one can obtain $L_{\gamma\gamma} \sim 10^{33}$ cm^{-2}s^{-1} at $z = W_{\gamma\gamma}/2E > 0.7$ (see next section). It is determined only by the "geometric" e$^-$e$^-$ luminosity. Using beams with smaller emittances one can get higher luminosity. Analyses of principle restrictions on luminosity of photon colliders have shown [13] (see sect.4) that at $2E \leq 5$ TeV one can obtain (in principle) $L_{\gamma\gamma} \geq 10^{35}$ cm^{-2}s^{-1}.

3 Current projects

Recently, two groups NLC [7] and TESLA/SBLC [8] (and soon JLC) have published Conceptual Design Reports of their linear collider projects containing comprehensive appendixes devoted to $\gamma\gamma$, γe options. Below is a short review of these designs.

3.1 Collision schemes

Two collision scheme were considered. <u>scheme A</u> ("without deflection"). There is no magnetic deflection of spent electrons and all particles after the conversion region travel to the IP. The conversion point may be situated very close to the IP; <u>scheme B</u> ("with deflection"). After the conversion region, particles pass through a region with a transverse magnetic field ($B \sim 0.5$–1 T) where electrons are swept aside. Thereby one can achieve more or less pure $\gamma\gamma$ or γe collisions.

In both schemes, the removal of the disrupted spent beam is done by using the crab crossing scheme with the crossing angle about 30 mrad. The maximum disruption angle does not exceed 10 mrad and outgoing beams travel outside the final quads located at a distance about 2 m from the IP.

3.2 Conversion region. Requirements to lasers. Optics at the IP.

The conversion region is situated at the distance $b \sim 1.5\gamma\sigma_y = 0.5$–1.5 cm from the IP. An optimum laser wave length for the collider with 2E = 500 GeV is about 1 μm (for $x = 4E_0\omega_0/m^2c^4 = 4.8$) and grows proportionally to the beam energy. The required flash energy for obtaining the conversion coefficient $k \sim 0.65$ is about 1–4 J for an electron bunch length $\sigma_z = 0.1$–0.5 mm, laser peak power is about 0.5–0.7 TW, average power is about 20 kW.

Obtaining such parameters is possible with either solid state lasers or free electron lasers. For $\lambda > 1$ μm ($E_0 > 250$–300 GeV) FEL is the only option seen now. The possible layout of optics near the IP is shown in fig 2.

3.3 Luminosity

In current projects, the $\gamma\gamma$ luminosity is determined by the "geometric" ee–luminosity. Due to the absence of beamstrahlung, beams in $\gamma\gamma$ collisions can have much smaller horizontal beam size than that in e^+e^- collisions, therefore the beta functions were taken as small as possible (some restrictions are posed by the Oide effect connected with chromatic aberrations due to synchrotron radiation in the final quads).

Typical $\gamma\gamma$ luminosity distribution is broad with its peak at maximum invariant masses at $z = W_{\gamma\gamma}/2E_0 \sim 0.8$ (for x=4.8). The region $z > 0.65$ is the most valuable
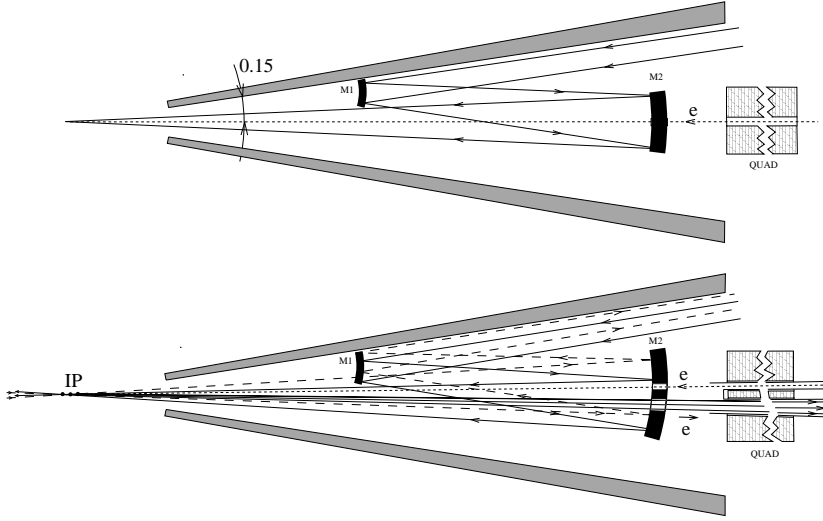
Figure 2: Layout of laser optics near the IP; upper - side view, down - top view, dashed lines – exit path of light coming from the left through one of the CP points (right to the IP), the distance between the IP and quads is about 2 m

part of luminosity due to high energy and high degree of polarization. The luminosity in this part is about 10% of the geometric ee luminosity.

The results of simulations for different projects are the following. For the "nominal" beam parameters (the same as in e^+e^- collisions) and the optimum final focus system the luminosity $L_{\gamma\gamma}(z > 0.65) \sim (0.8/1.2/0.7) \times 10^{33}$ cm^{-2}s^{-1} for NLC/TESLA/SBLC. The peak luminosity is also an important characteristic, it is approximately equal to $dL_{\gamma\gamma}/dz \sim 7L_{\gamma\gamma}(z > 0.65)/z_{max}$. These numbers are close for the schemes with and without magnetic deflection.

In the scheme without deflection, γe collisions can be studied simultaneously with $\gamma\gamma$ collisions. In this case the γe luminosity is even higher than $L_{\gamma\gamma}$ by a factor of 1.5 (this is valid only for considered beam parameters; for very small beam sizes $L_{\gamma e} \ll L_{\gamma\gamma}$ due to beam–beam repulsion). The magnetic deflection allows to obtain almost clean γe collisions with FWHM$\sim$7%.

There are several possibilities for increasing luminosity.

1) Reduction of the horizontal emittance by optimizing the damping rings. For example, at the TESLA, the decrease in ϵ_{nx} by a factor 3.5 leads to an increase in $L_{\gamma\gamma}$ up to 3×10^{33} cm^{-2}s^{-1}.

2) One can use the low emittance RF-photoguns instead of damping rings. Unfortunately, even with best photoguns the luminosity will be somewhat lower than that with damping rings. However, there is one possible solution. The normalized emittance in photoguns is approximately proportional to the number of particles in the electron bunch. It seems possible to merge (using some difference in energies) many ($N_g \sim 5 - 10$) low current beams with low emittances to one high current beam with the same transverse

emittance. This gives the gain in luminosity more than by a factor N_g in comparison with one photogun ("more" because the lower emittance allows smaller beta functions due to the Oide effect). Joining beams from five photoguns with experimentally achieved parameters leads at TESLA/SBLC to $L_{\gamma\gamma} = (3\text{--}4) \times 10^{33}$ cm^{-2}s^{-1}.

For a considerable step in luminosity the beams with much lower emittances are required that needs the development of new approaches such as a *laser cooling* [12] (sect.4.2). Potentially this method allows to attain the geometric luminosity by two orders higher than those achievable by the methods discussed above. One example [8] of the luminosity distributions for the "super" TESLA with round beams and emittances by a factor 50 lower than that achieved with RF–photoguns is shown in fig 3. Beam parameters and resulting luminosities are given below.
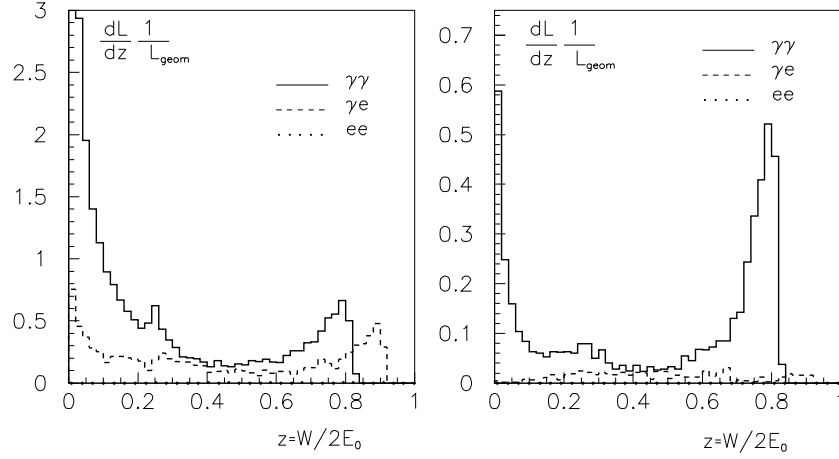

Figure 3: Luminosity spectra for the "super" TESLA parameters (see the text). Left – without the deflection; right – $\gamma\gamma$ collisions with the magnetic deflection ($B = 0.5$ T)

Electron beam parameters of the "super" TESLA
$N = 3.63 \times 10^{10}$, $\sigma_z = 0.5$ mm, $2E = 500$ GeV, $f = 5.65$ kHz,
$\epsilon_{nx} = \epsilon_{ny} = 0.2 \times 10^{-6}$ m rad, $\beta_x = \beta_y = 0.5$ mm, $\sigma_x = \sigma_y = 14$ nm,
$L_{geom} = 2 \times 10^{35}$ cm^{-2} c^{-1}
Luminosities without deflection: $b = \gamma\sigma_y = 0.7$ cm,
$L_{\gamma\gamma} = 1.15 \times 10^{35}$, $L_{\gamma\gamma}(z > 0.65) = 1.5 \times 10^{34}$ cm^{-2} c^{-1},
$L_{\gamma e} = 3.6 \times 10^{34}$, $L_{\gamma e}(z > 0.65) = 1.2 \times 10^{34}$ cm^{-2} c^{-1},
Luminosities with magnetic deflection: $b = 1.5$ cm, $B = 0.5$ T,
$L_{\gamma\gamma} = 2 \times 10^{34}$, $L_{\gamma\gamma}(z > 0.65) = 1 \times 10^{34}$ cm^{-2} c^{-1},
$L_{\gamma e} = 2.5 \times 10^{33}$, $L_{\gamma e}(z > 0.65) = 6 \times 10^{32}$ cm^{-2} c^{-1},
Results are impressive: $L_{\gamma\gamma}(z > 0.65) = (1\text{--}1.5) \times 10^{34}$ cm^{-2}s^{-1} (2–3 times higher than those in e$^+$e$^-$ collisions). It is not the limit (see sect.4.3)

4 New ideas

4.1 Laser cooling

Recently [12], a new method was considered — laser cooling of electron beams — which allows, in principle, to reach $L_{\gamma\gamma} \geq 10^{35}$ cm^{-2}s^{-1}.

The idea of laser cooling of electron beams is very simple. During a collision with optical laser photons (in the case of strong field it is more appropriate to consider the interaction of an electron with an electromagnetic wave) the transverse distribution of electrons (σ_i) remains almost the same. Also, the angular spread (σ_i') is almost constant, because for photon energies (a few eV) much lower than the electron beam energy (several GeV) the scattered photons follow the initial electron trajectory with a small additional spread. So, the emittance $\epsilon_i = \sigma_i \sigma_i'$ remains almost unchanged. At the same time, the electron energy decreases from E_0 down to E. This means that the transverse normalized emittances have decreased: $\epsilon_n = \gamma\epsilon = \epsilon_{n0}(E/E_0)$. One can reaccelerate the electron beam up to the initial energy and repeat the procedure. Then after N stages of cooling $\epsilon_n/\epsilon_{n0} = (E/E_0)^N$ (if ϵ_n is far from its limit).

Some possible sets of parameters for the laser cooling are: $E_0 = 4.5$ GeV, $l_e = 0.2$ mm, $\lambda = 0.5$ μm, flash energy $A \sim 10$ J. The final electron bunch will have an energy of 0.45 GeV with an energy spread $\sigma_E/E \sim 13\%$, the normalized emittances $\epsilon_{nx}, \epsilon_{ny}$ are reduced by a factor 10. A two stage system with the same parameters gives 100 times reduction of emittances. The limit on the final emittance is $\epsilon_{nx} \sim \epsilon_{ny} \sim 2 \times 10^{-9}$ m rad at $\beta_i = 1$ mm. For comparison, in the TESLA (NLC) project the damping rings have $\epsilon_{nx} = 14(3) \times 10^{-6}$ m rad, $\epsilon_{ny} = 25(3) \times 10^{-8}$ m rad.

This method requires a laser system even more powerful than that for e $\rightarrow \gamma$ conversion. However, all the requirements are reasonable taking into account fast progress of laser technique and time plans of linear colliders. A multiple use of the laser bunch can reduce considerably an average laser power.

4.2 Stretching of laser focus depth

The laser and electron beams interact with each other most efficiently when laser and electron beams have the same duration and the depth of laser focus (Rayleigh length) is somewhat shorter than the beam length. It turns out that in many cases, the density of laser photons is so high that instead of the Compton scattering an electron interacts simultaneously with many photons (synchrotron radiation). This is not desirable since in the regime of strong field ($eB\lambda > mc^2$) the spectrum of scattered photons after conversion region is not so peaked as in the Compton scattering case. In the method of laser cooling the strong field leads to higher values of minimum emittance and higher polarization loss. Of course, one can take laser bunch longer to keep collision probability constant and the density of photons below the critical value. However, in this case, the laser flash energy should be larger than that under optimum conditions given in the beginning of this paragraph. Due to this nonlinear QED effect the laser flash energy required for photon colliders should grow proportionally to the collider energy [4],[5].

Recently [12], it was found how to avoid this problem. In the suggested scheme the focus depth is stretched without changing the radius of this area. In this case, the collision probability remains the same but the maximum value of the field is smaller. The solution is based on use of chirped laser pulses and chromaticity of the focusing system [1]. In this scheme, the laser target consists of many laser focal points (continuously) and light comes to each point exactly at the moment when the electron bunch is there. One can consider that a short electron bunch collides on its way sequentially with many short light pulses of length $l_\gamma \sim l_e$ and focused with $2Z_R \sim l_e$.

The required flash energy in the scheme with a stretched laser focus is determined only by diffraction and at the optimum wave length (x=4.8) does not depend on the collider energy. The stretching of laser focus enables a substantial decrease in flash energy in the method of laser cooling, to achieve minimum emittances and to conserve polarization of electron beams.

4.3 Ultimate luminosity and energy of photon colliders

The only collision effect restricting $\gamma\gamma$ luminosity at photon colliders is the coherent pair creation which leads to the conversion of a high energy photon into e^+e^- pair in the field of opposing electron beam [10],[4],[5]. There are three ways to avoid this effect: a) to use flat beams; b) to deflect the electron beam after conversion at a sufficiently large distance from the IP; c) under certain conditions (low beam energy, long bunches) the beam field at the IP is below the critical one due to the repulsion of electron beams [11]. The problem of ultimate luminosities for different beam parameters and energies was analyzed recently in ref. [13] analytically and by simulation. Resume is the following.

The maximum luminosity is attained when the conversion point is situated as close as possible to the IP: $b = 3\sigma_z + 0.04E$[TeV] cm (here the second term is equal to the minimum length of the conversion region). In this case, the vertical radius of the photon beam at the IP is also minimum: $a_\gamma \sim b/\gamma$ (assuming that the vertical size of the electron beam is even smaller). An optimum horizontal beam size (σ_x) depends on the beam energy, number of particles in a bunch and bunch length. The dependence of the $\gamma\gamma$ luminosity on σ_x for various energies and number of particles in a bunch is shown in fig.4. The bunch length is fixed to be equal to 0.2 mm. The collision rate is calculated from the total beam power which is equal to 15E[TeV] MW (close to that in current projects). In the fig.4 we see that at low energies and small number of particles the luminosity curves follows their natural behaviour $L \propto 1/\sigma_x$ while at high energy and large number of particles in a bunch the curves make zigzag which is explained by $\gamma \rightarrow e^+e^-$ conversion in the field of the opposing beam.

What is remarkable in these results? First of all, the maximum attainable luminosities are huge. At low energies there are no coherent pair creation even for a very small σ_x when the field in the beam is much higher than the critical field $B_{cr} = \alpha e/\gamma r_e^2$. This is

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[1]In a chirped pulse the wave length is linearly depends on longitudinal position. Such pulses are obtained and used now in all short-pulse lasers.

explained by the fact that beams during the collision are repulsing each other so that the field on the beam axis (which affects on high energy photons) is below the critical field. It means that the $\gamma\gamma$ luminosity is simply proportional to the geometric electron-electron luminosity (approximately $L_{\gamma\gamma}(x > 0.65) \sim 0.1 L_{ee}$) for $\sigma_x, \sigma_y > b/\gamma \sim 3\sigma_z/\gamma + 0.2$ nm. For the energies 2E< 2 TeV which are in reach of next generation of linear colliders the luminosity limit is much higher than it is required by our scaling low given by Eq.1.

4.4   Backgrounds

One of important problems at high luminosities is a background due to relatively large total cross section $\sigma_{\gamma\gamma\to hadrons} \sim 5 \times 10^{-31}$ cm^2.

The average number of hadron events/per bunch crossing is about one at $L_{\gamma\gamma}(z > 0.65) = 2 \times 10^{34}$ cm^{-2}s^{-1} at the typical collision rate 10 kHz. However, in the scheme without deflection the total $\gamma\gamma$ luminosity is larger than the "useful" $L_{\gamma\gamma}(z > 0.65)$ by a factor 5–10. This low energy collisions increase background by a factor 2–3 [8].

Let us assume the photon collider luminosity to be $L_{\gamma\gamma}(z > 0.65) \sim 10^{35}$ cm^{-2}s^{-1} (top
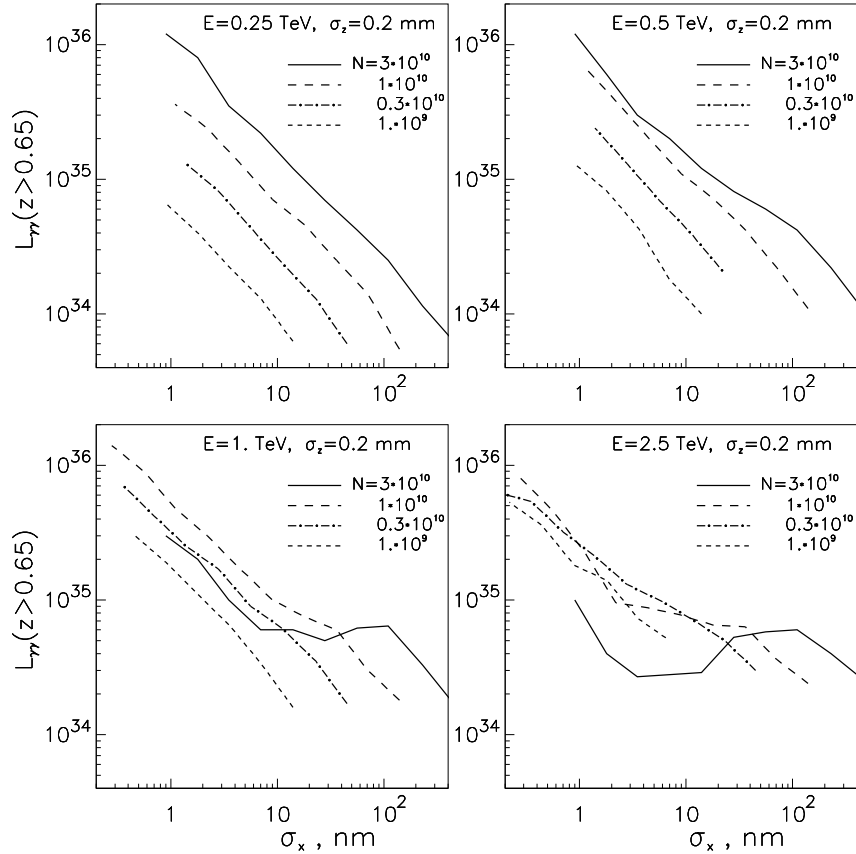

Figure 4: Dependence of the $\gamma\gamma$ luminosity on the horizontal beam size for $\sigma_z = 0.2$ mm, see comments in the text.

of our dreams), this leads to about 15 (effectively) high energy $\gamma\gamma \to hadron$ events per bunch crossing. Approximately the same number ($\sim$30) of events/collision is expected in detectors at the LHC . However, there is an important difference between pp and $\gamma\gamma$ colliders: in the case of an interesting event (high P_t jets or leptons) the total energy of final products at photon colliders is equal to E_{cm}, while at proton colliders it is only about $(1/6)E_{cm}$. In comparison with the pp collider the ratio of the signal to background at photon colliders is better by a factor of 6 at the same number of hadronic events per crossing. Note, however, that at NLC and JLC the time between collisions is only about 1.5 ns and background from a few neighbouring events will overlap. At more realistic top $\gamma\gamma$ luminosities about $L_{\gamma\gamma}(z > 0.65) \sim 10^{34}$ cm^{-2}s^{-1} even with this fact the background conditions will be acceptable. These arguments and detailed simulation [8] show that the problem of hadronic background is not dramatic for photon colliders.

Acknowledgments

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